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Aerobic treatment of wastewaters in the inverse fluidised bed biofilm reactor

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Abstract

The aerobic treatment of wastewaters was investigated in the inverse fluidised bed biofilm reactor (IFBBR) in which polypropylene particles of density 910 kg/m^3 were fluidised by an upward cocurrent flow of gas and liquid. Measurements of chemical oxygen demand (COD) versus residence time t were performed for various ratios of settled bed volume to bioreactor volume (V_b/V_R) and air velocities u to determine the optimal operating parameters for a reactor, that is, the values of (V_b/V_R), u and t for which the largest reduction in COD occurred.

The largest COD removal was attained when the reactor was controlled at the ratio (V_b/V_R) = 0.55 and an air velocity u = 0.021 m/s. Under these conditions, the value of COD was practically at steady state for times greater than 25 h. In the wastewater treatment conducted in a reactor optimally controlled at (V_b/V_R) = 0.55, u = 0.021 m/s and t = 25 h, a decrease in COD from 27,650 to 450 mg/l was obtained, that is, approximately a 98% COD reduction was achieved. The pH was controlled in the range 6.5–7.0 and the temperature was maintained at 28–30 °C.

The biomass loading in a reactor depended on the ratio (V_b/V_R) and an air velocity u. In the cultures cultivated after change in (V_b/V_R) at a set u, the steady-state mass of cells grown on the particles was achieved after approximately 3 days of operation. With change in u at a set (V_b/V_R), the new steady-state biomass loading occurred after cultivation for about 2 days.

Keywords: Inverse fluidised bed biofilm reactor; Aerobic wastewater treatment; Three-phase fluidised bed biological reactor; Biological wastewater treatment; Low density biomass support

1. Introduction

The application of a fluidised bed technique to biological wastewater treatment has brought a remark breakthrough [1–6]. Treatment of industrial wastewaters requires a great deal of space when using systems based on activated sludge in which the retention time is many days [3–5]. On the other hand, a fluidised bed biofilm reactor (FBBR) is capable of achieving treatment in low retention time because of the high biomass concentrations that can be achieved in a reactor [1,3,5]. The bed, consisting of small particles, offers a vast surface area for microbial growth in the state of fluidisation. This enables far greater microbial concentration than that maintained in the activated sludge process and in the conventional fixed bed systems such as a trickling filter, rotating disc filter and submerged contact oxidation.

The application of a low density (matrix particle density smaller than that of liquid) biomass support in a reactor allows the control of biomass loading on particles and provides the high oxygen concentration in the reacting liquid media [1,7–9]. In a reactor with low density particles, fluidisation can be conducted either by an upward cocurrent flow of gas and liquid through a bed or by a downward flow of liquid and countercurrent upward flow of gas (Fig. 1) [1,8]. In the former, fluidisation is achieved by an upward flow of gas whereby the gas bubbles make the bed expanding downwards into the less dense mixture of gas and liquid [1,8]. In the latter, the bed is fluidised by a downward flow of a liquid counter to the net buoyancy force of the particles [7,9,10]. At a small flow of the liquid, not sufficient to counter to the net buoyancy force, fluidisation can be achieved by an adequate upward flow of the gas. Such type of fluidisation, where fluidised bed expands downwards, is termed the *inverse fluidisation*.

Abbreviations: COD, chemical oxygen demand (mg/l); FBBR, fluidised bed biofilm reactor; IFBBR, inverse fluidised bed biofilm reactor; TFBBR, three-phase fluidised bed biofilm reactor

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Nomenclature

D	dilution rate (h^{-1})
t	mean residence time (h)
u	superficial upflow air velocity (m/s)
V_b	volume of settled bed (m^3)
V_R	reactor volume (m^3)
ε	air hold-up (dimensionless)

Nikolov and Karamanev [10] have reported that a biomass loading was successfully controlled in an inverse fluidised bed biofilm reactor (IFBBR), in which low density particles were fluidised by downflow of the liquid. Rusten et al. [9] have demonstrated that a practically constant biomass loading was attained in a reactor containing low density particles made of polyethylene. Sokół and Halfani [8] have achieved the steady-state biomass loading in a three-phase fluidised bed biofilm reactor (TFBBR) containing particles made of polypropylene. In other work, Sokół and Halfani [11] have recommended the use of a TFBBR with light particles for aerobic biological treatment of industrial wastewaters.

The aim of this work was to investigate the aerobic treatment of wastewater in a IFBBR, in which particles made of polypropylene of density 910 kg/m^3 were fluidised by an upward cocurrent flow of gas and liquid through a bed. Experiments on the carbonaceous COD reduction were performed for various ratios of settled bed volume to reactor volume (V_b/V_R), air velocities u and mean residence times t to determine the values of (V_b/V_R), u and t for which the largest reduction in COD occurred.

2. Wastewater treatment in a FBBR with light biomass support

The FBBRs, in which the biomass is spontaneously fixed on particles, are among the most effective apparatuses used in wastewater treatment [1–8]. The large biofilm–liquid interfacial area, high interfacial velocities and good mass transfer characteristics are the main advantages of this type of reactors. A FBBR outperforms other reactor configurations used in wastewater treatment such as the activated sludge system (continuous stirred tank reactor) and packed-bed (or trickling-filter) reactor [1,5,8]. The superior performance of the FBBR stems from the very high biomass concentration (30–40 kg/m^3) that can be achieved due to immobilisation of cells onto and/or into the solid particles [5].

A FBBR has been successfully applied to aerobic biological treatment of industrial and domestic wastewaters [4,5,8]. A fluidised bed biological treatment technology owes its high rate success to much higher surface area and biomass concentration than those that can be achieved in the conventional treatment processes [1,3,5]. The use of biomass support allows the partial replenishment of the fluidised bed without interrupting the operation in order to maintain high microbial activity. Once fluidised, the particles provide a large surface area for biofilm formation and growth. Each particle eventually becomes covered with biofilm and the vast growth surface afforded by the media results in a biomass concentration approximately an order of magnitude greater than that maintained in a suspended growth system [1,5].

However, the uncontrolled growth of the fixed biomass changes the hydrodynamic characteristics of each bioparticle (support particle covered by biofilm) and the whole fluidised bed. It also affects the mass transfer of substrate into the biofilm. The maximum penetration depth of substrate into the biofilm of the mixed aerobic cultures used for wastewater treatment is 50–200 μm [7]. The excessive growth of biomass on support media can lead to the channelling of bioparticles in fluidised bed since the biomass loading can increase to such an extent that the bioparticles began to be carried over from a reactor [2,8].

Nikolov and Karamanev [10] have studied the aerobic wastewater treatment and the ferrous iron oxidation in a IFBBR. The reactor was the combination of an inverse fluidised bed and

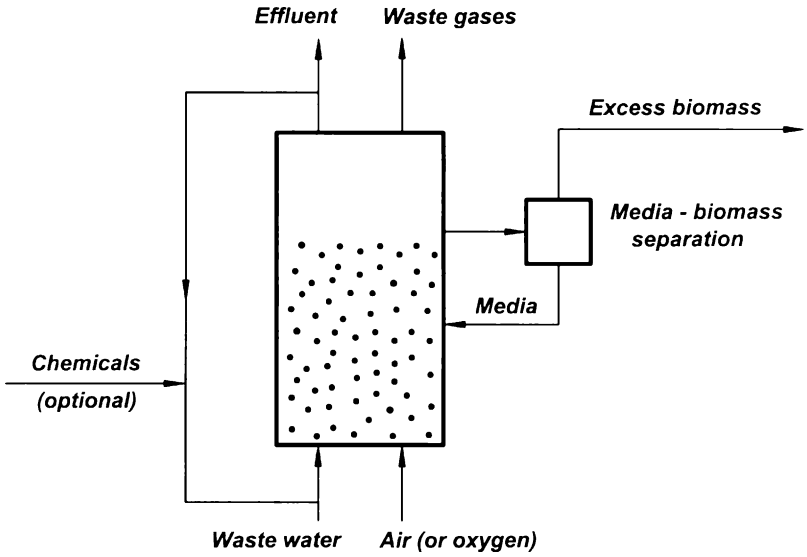

Fig. 1. Schematic illustration of the inverse fluidised bed biofilm reactor (IFBBR).

an airlift draft tube (Fig. 2). The air, introduced at the bottom of the inner tube, created a recirculation of the liquid. The downflow in the annulus expanded the bed of low density particles, thus forming an inverse fluidised bed. In the wastewater treatment experiments, an aqueous glucose solution (0.4–12 g of glucose/l) and a mixed culture of aerobic heterotrophic microorganisms were used. Polyethylene granules with diameter 2–3 mm were used for fixation of the bacteria. In the ferrous iron oxidation, aqueous solutions of $FeSO_4$, containing 3–4 g/l Fe^{2+} and sulphuric acid for control of the pH value in the range of 2.0–2.5, were used as substrate. The bacterial culture *Thiobacillus ferrooxidants* used in experiments was isolated from drainage waters. Polystyrene spheres with diameter 0.8–1 mm and density 330 kg/m^3 were utilised as support media.

The researchers [10] have reported that the reaction rate at a 90% conversion was 80 mg glucose consumed per litre reactor volume per hour. The maximum rate achieved was 1000 mg glucose/(l reactor h). The results were compared with those obtained in the basic draft tube airlift reactor, that is, in the same reactor but without polyethylene particles. The IFBBR was 3.6 times more effective at a glucose conversion of 90%. The ratio between the maximal glucose uptake rates was even greater, namely: 14.8 times. In the ferrous ions (Fe^{2+}) oxidation at a value of 70% conversion, the oxidation rate was 0.7 g Fe^{2+}/(l reactor h) with the maximum value of 2.1 g Fe^{2+}/(l reactor h). Compared with the data obtained in the reactor under identical conditions with only suspended bacteria, these values were 4.4 and 10 times larger, respectively.

Rusten et al. [9] have applied a biomass support made of ethylene in a FBBR used for treatment of wastewaters from dairy and food industry. With this support, a considerably higher treatment efficiency was achieved than that obtained in a reactor with a sand support. The biomass loading was relatively low and practically constant over the entire period of a 3-month operation, and yet, the reactor performed very well with approximately a 95% removal of total COD. Particle–particle and particle–wall collisions sloughed off excess biomass.

Sokół [12] has reported a 95% removal of total COD in aerobic treatment of brewery wastewater in a TFBBR with low density biomass support. In other work, Sokół [13] has achieved a 90% COD reduction in aerobic treatment of highly toxic refinery wastewater in a TFBBR containing particles made of polypropylene. Sokół and Korpal [1] have reported a 98% COD reduction in treatment of phenolic wastewaters in a TFBBR in which particles made of polypropylene were fluidised by an upward cocurrent flow of gas and liquid.

3. Experimentation

3.1. Experimental set-up

Experiments were performed in the apparatus shown in Fig. 3. The fluidised bed section (9) had a 20 cm internal diameter and was 6 m high. It was ended by a disengaging cap (10) with a 60 cm internal diameter and a height of 80 cm. A growing medium, stored in reservoir (1), was pumped into the bottom of the reactor by a centrifugal pump (5). Before entering the

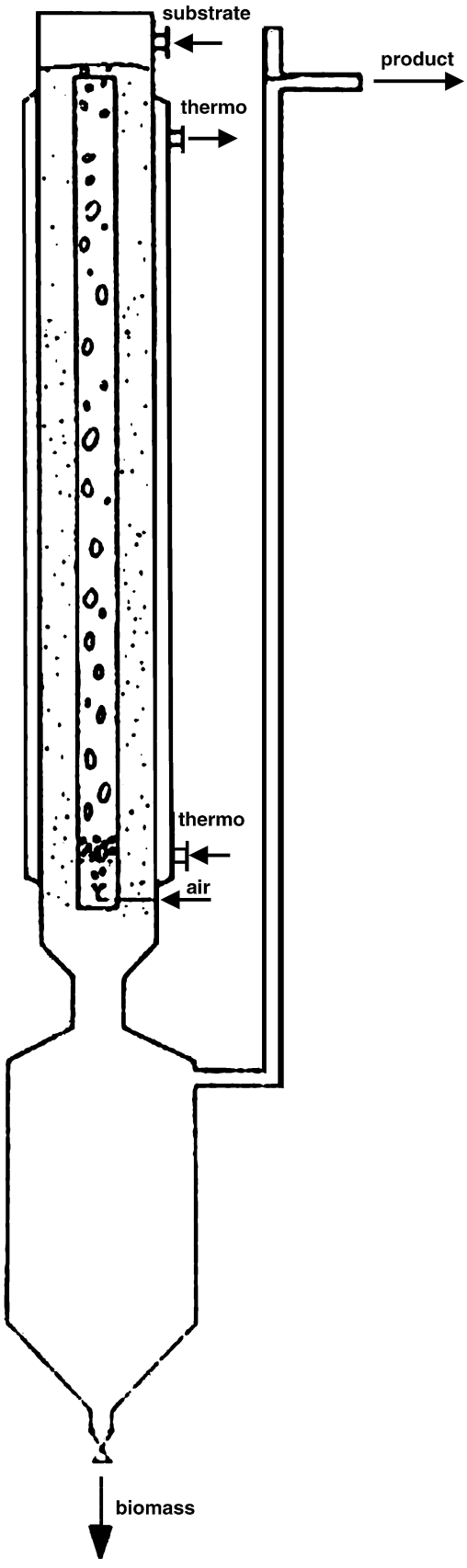

Fig. 2. Schematic of the inverse internal loop airlift fluidised bed biofilm reactor [10].

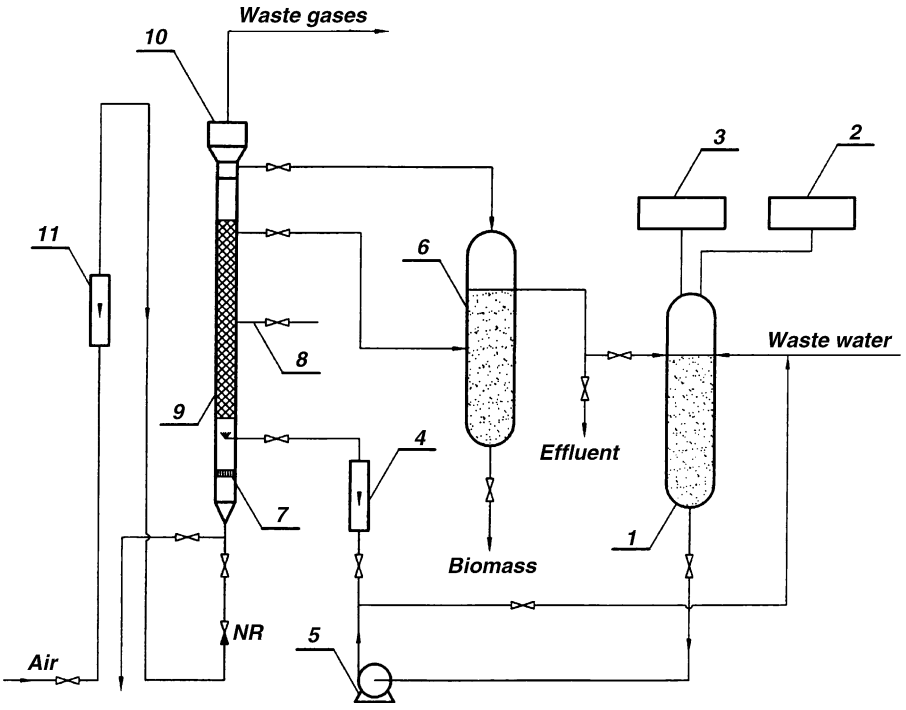

Fig. 3. Schematic diagram of the experimental apparatus: (1) reservoir; (2) temperature control system; (3) pH control system; (4) liquid rotameter; (5) pump; (6) intermediate reservoir; (7) air distributor; (8) sampling; (9) fluidised section; (10) disengaging section; (11) air rotameter.

bed, the liquid was mixed with air by means of a sparger. The biomass sloughed off from the particles was separated from the effluent in a vessel (6) and removed from the system. The air was introduced to the bed through a distributor (7) whose plate had 200 mm × 4 mm diameter holes on a triangular pitch. The air-flow rate was measured by a rotameter (11) and controlled by a needle valve. The flow rate of the liquid was measured using a rotameter (4) and controlled by a ball valve. The pH was adjusted by a control system (3), consisting of a pH-meter and micropumps supplying base or acid as required. The temperature control system (2) consisted of a coil with cold water and an electric heater coupled with a contact thermometer.

The biomass support was the polypropylene particles of density 910 kg/m^3 which are described elsewhere [1].

3.2. Feed and microorganisms

The growing medium was the refinery wastewater whose composition is given in Table 1. The wastewater was enriched in mineral salts by adding the following (mg/l): $(NH4)_2SO_4$ 500; KH_2PO_4 200; $MgCl_2$ 30; NaCl 30; $CaCl_2$ 20; and $FeCl_3$ 7 as recommended by Sokol [14], and Sokol and Migiro [15].

The inoculum was the activated sludge taken from the biological treatment unit operated at the refinery.

3.3. Methodology

Sokół and Halfani [8] have reported that the largest values of air hold-up ε, and thus the largest interfacial area were obtained when a TFBBR with polypropylene particles was controlled at ratio (V_b/V_R) in the range 0.50–0.60. Sokół [13] has established that the optimal value of (V_b/V_R) for a TFBBR when used in treatment of refinery wastewater was equal to 0.55. Therefore, in this study experiments were conducted for the ratios (V_b/V_R) equal to 0.50, 0.55 and 0.60. This was to cover the searched range of (V_b/V_R) from 0.50 to 0.60 in step 0.05 which is sufficient accuracy for industrial practice.

3.3.1. Biomass cultivation

The particles and the growing medium were introduced into the reactor to give a ratio $(V_b/V_R) = 0.50$. To start growth of the microorganisms on the particles, a batch culture was first initiated by introducing about 15 l of the inoculum into the reactor. Then the culture was incubated for approximately 48 h to encourage cell growth and the adhesion of freely suspended

Table 1
Composition of a wastewater (feed) and effluent from a reactor optimally controlled at $(V_b/V_R) = 0.55$, $u = 0.021$ m/s and $t = 25$ h

Constituent	Concentration × 10^3 mg/l	
	Feed	Effluent
Phenol	1898	2.92
o-Cresol	4527	0.78
m-Cresol	2688	0.64
Isopropylphenol	751	1.35
2,4-Dimethylphenol	1512	0.37
2,6-Dimethylphenol	326	0.52
3,4-Dimethylphenol	598	0.24
3,5-Dimethylphenol	2017	0.48
Benzene	994	2.91
Toluene	1002	2.68
o-Xylene	349	22.15
C_3-phenyl	83	23.21

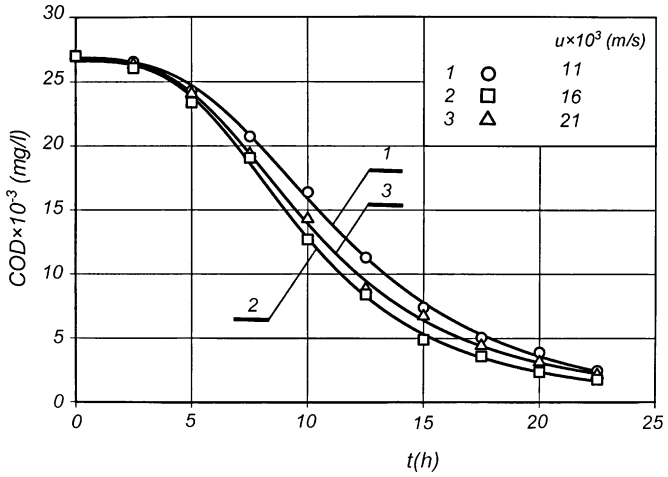

Fig. 4. Dependence of COD values on time (t) for ratio $(V_b/V_R) = 0.50$ and various air velocities (u).

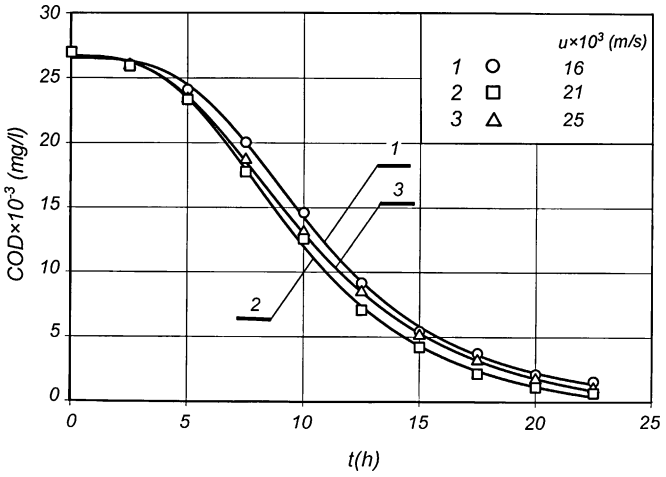

Fig. 5. Relationship between COD values and time (t) for ratio $(V_b/V_R) = 0.55$ and various air velocities (u).

biomass on the support. The air was supplied at the flow rate of 2×10^{-2} m^3/s and this was found to be sufficient for biomass growth. The pH was controlled in the range 6.5–7.0 and the temperature was maintained at 28–30 °C.

When the biofilm had begun to grow on the particles, the growing medium was started to be pumped into the reactor at a dilution rate $D = 0.40\,h^{-1}$. This value of D corresponded to the smallest time t applied for the ratio $(V_b/V_R) = 0.50$ ($t = 1/D = 2.5$ h in Fig. 4). Next, the air velocity was set at the smallest value applied for the $(V_b/V_R) = 0.50$ ($u = 0.011$ m/s in Fig. 4) and the cultivation was continued until the constant biomass loading was achieved in a reactor. The occurrence of the steady-state biomass loading was established by weighting the mass of cells grown on the support. The biomass was scraped from sample particles and dried at temperature 105 °C for 1 h. It was considered that the steady state occurred when the weight of biomass in two consecutive samples differed less than 5%. The constant biomass loading was attained in a reactor after the cultivation for approximately 3 days.

3.3.2. *Determination of the optimal operating parameters*

When the steady-state biomass loading was achieved in a reactor, a sample liquid was withdrawn from the bioreactor and COD was measured by the procedure recommended by Verstraete and van Vaerenbergh [16]. It was established that once the constant biomass loading occurred in a reactor, the value of COD was practically at steady state.

Next, the air velocity was increased stepwise to its next value of u applied for $(V_b/V_R) = 0.50$ ($u = 0.016$ m/s in Fig. 4) and the cultivation was continued until the new steady-state biomass loading was achieved. When this was attained, COD was measured by the method mentioned earlier [16]. These experiments for $(V_b/V_R) = 0.50$ were conducted for all values of u shown in Fig. 4.

Then the dilution rate was decreased stepwise to its next value applied for $(V_b/V_R) = 0.50$ ($t = 1/D = 5$ h in Fig. 4) and the air velocity was re-set to its smallest value applied for the $(V_b/V_R) = 0.50$ ($u = 0.011$ m/s in Fig. 4). The cultivation was continued until the steady-state biomass loading was achieved. When this occurred, COD was measured following the procedure mentioned earlier [16]. These experiments were conducted for all air velocities u and times t shown in Fig. 4. The results are given in Fig. 4.

The above experiments were also performed for the ratios (V_b/V_R) equal to 0.55 and 0.60. In order to get the ratio $(V_b/V_R) = 0.55$, an adequate volume of biomass-free particles was added to a reactor at the end of experimentation for $(V_b/V_R) = 0.50$. Similarly, the ratio $(V_b/V_R) = 0.60$ was obtained by the addition of fresh particles to a reactor at the end of experimentation for $(V_b/V_R) = 0.55$. The results of the experiments are shown in Figs. 5 and 6.

In order to establish time t for which the value of COD was practically at steady state, experiments on the carbonaceous COD reduction were conducted for these values of (V_b/V_R) and u for which the largest COD removals were achieved in runs shown in Figs. 4–6. The results of experiments are shown in Fig. 7.

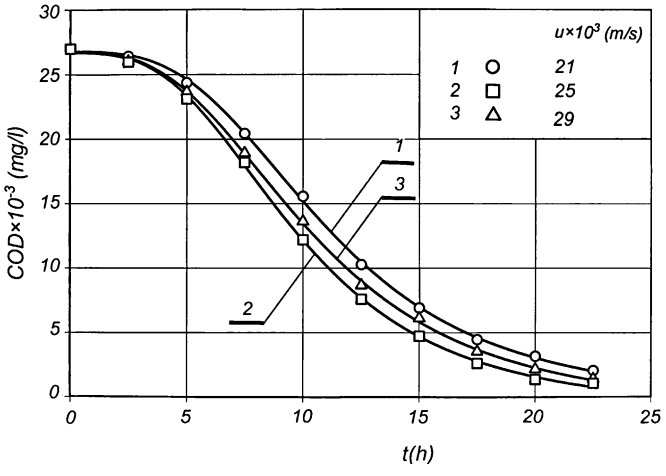

Fig. 6. Dependence of COD values on time (t) for ratio $(V_b/V_R) = 0.60$ and various air velocities (u).

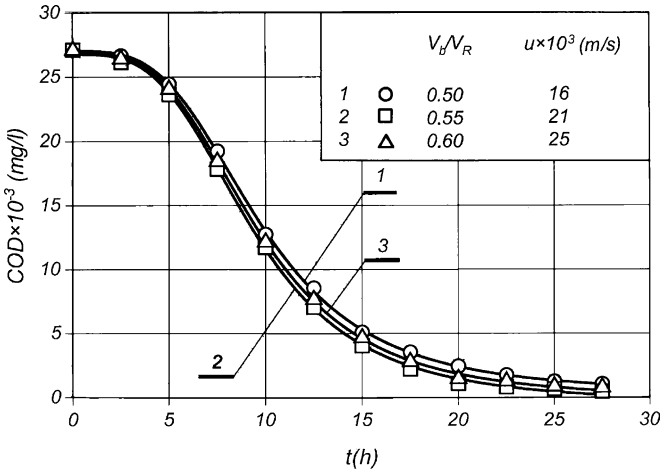

Fig. 7. Relationship between COD values and time (t) for wastewater treatment conducted in a reactor controlled at the values of (V_b/V_R) and u for which the greatest COD removals occurred in runs shown in Figs. 4–6.

4. Results and discussion

A decrease in COD values, for a set time t, depended on the ratio (V_b/V_R) and an air velocity u (Figs. 4–6). The largest reduction in COD was attained at (V_b/V_R) = 0.55. An increase in COD removal with an increase in the (V_b/V_R) from 0.50 to 0.55 can be attributed to the fact that for increasing (V_b/V_R), more biomass grown on the particles participated in degradation of the constituents of the wastewater [5,13]. On the other hand, a decrease in COD removal observed with an increase in (V_b/V_R) from 0.55 to 0.60 was due to the fact that in this case, a significant volume of the reactor was occupied by the support media, and consequently the aeration characteristics of the bed has worsened [5,8].

A decrease in COD values, for a set time t and ratio (V_b/V_R), depended on the air velocity u. A reduction in COD initially increased monotonically, and then decreased with an increase in u (Figs. 4–6). For the ratio (V_b/V_R) = 0.50, the largest reduction in COD occurred for u = 0.016 m/s (Fig. 4). This can be explained by the fact that with an increase in u up to 0.016 m/s, an interfacial (air–liquid) area increased [17], and consequently the amount of the oxygen supplied for biomass growth increased [8,11]. For the u smaller than 0.016 m/s, oxygen was the limiting factor for biomass growth. An increase in the u above 0.016 m/s had no effect on reduction in COD values (Fig. 4). Thus, for the ratio (V_b/V_R) = 0.50 and the air velocities greater than 0.016 m/s, the degradation rate of the constituents of the wastewaters was the controlling factor of the treatment process [8,11].

The value of u for which the largest decrease in COD was obtained for a set t, depended on the ratio (V_b/V_R), and hence on volume V_b of the particles applied in the reactor (Figs. 4–6). With the V_b increasing, the value of u increased. Thus, a large volume of the support can lead to an increase in the amount of the air required for biomass growth, and consequently to an increase in the resulting energy cost [18].

The value of COD was practically at steady state for times t greater than 25 h (Fig. 7). The largest COD removal occurred when the reactor was operated at (V_b/V_R) = 0.55 and u = 0.021 m/s. A decrease in COD from 27,650 to 450 mg/l, i.e. a 98% COD reduction, was obtained when a reactor was optimally controlled at (V_b/V_R) = 0.55, u = 0.021 m/s and t = 25 h.

The application of low density particles allowed the control of a biomass loading in a reactor. In the cultures cultivated after change in a ratio (V_b/V_R) at a set u, the constant mass of cells grown on the particles was attained after approximately 6 days operation. For a set (V_b/V_R), the biomass loading depended on the air velocity u. With change in u, the new steady-state biomass loading on the support occurred after the culturing for about 2 days. The biomass loading was practically constant over the entire period of experimentation for this u which was set as the last.

5. Conclusion

(1) COD removal depended on ratio (V_b/V_R), air velocity u and residence time t. For set t and u, reduction in COD initially increased, and then decreased with an increase in (V_b/V_R), attaining the largest value at (V_b/V_R) = 0.55. Similarly, for set t and (V_b/V_R), reduction in COD initially increased monotonically, and then decreased with an increase in u. These changes have been attributed to interplay of interfacial (gas–liquid) area and oxygen limitations.

(2) The largest COD removal was achieved when the reactor was controlled at the ratio (V_b/V_R) = 0.55, air velocity u = 0.021 m/s and residence time t = 25 h. Thus, these values of (V_b/V_R), u and t can be considered as the optimal operating parameters for the inverse fluidised bed biofilm reactor (IFBBR) when used in refinery wastewater treatment.

(3) A decrease in COD from 27,650 to 450 mg/l, i.e. a 98% COD reduction, was achieved in wastewater treatment conducted in a reactor optimally controlled at (V_b/V_R) = 0.55, u = 0.021 m/s and t = 25 h. The pH was controlled in the range 6.5–7.0 and the temperature was maintained at 28–30 °C.

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